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Synthesis of novel interlocked systems utilizing a palladium complex with 2,6-pyridinedicarboxamide-based tridentate macrocyclic ligand

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Abstract—A new protocol for the high yield synthesis of interlocked molecules is described. Palladium(II) complex including a 2,6-pyridinedicarboxamide-based tridentate macrocycle **2** was allowed to react with a 2,6-disubstituted pyridine derivative bearing two hydroxyl groups at both termini **3b** to yield the corresponding Pd(II) complex **4b** quantitatively. An acid catalyzed end-capping of **4b** with a bulky isocyanate gave Pd(II) complex **5b** in 96% yield, which was treated with carbon monoxide to afford [2]rotaxane **6b** quantitatively.

In 1983, Sauvage and Dietrich-Buchecker's pioneering work on transition metal-templated synthesis of catenane[1] opened a new field for interlocked architectures such as catenanes, rotaxanes, and knots.[2] Their protocol relies on the preferred tetrahedral geometry of Cu(I)–phenanthroline complexes to create interlocked systems.[3] Since the development, several methods for 'directed' synthesis of interlocked molecules have been reported to date, including the utilization of π-stacking interaction and hydrogen-bonding interaction.[4] The components of catenates or rotaxanates are locked by their metal centers in fixed positions that can be even controlled by some external stimuli, whereas those of interlocked molecules assembled by hydrogen-bonding interaction or π-stacking interaction exhibit a continuous range of dynamic properties. Hence, the interlocked molecules assembled by transition metal templates are attractive particularly from viewpoints of the control over relative motion of their components such as 'shuttling' and 'rotation', which could be applied to molecular devices.[5]

We developed previously a series of *N*-heterocyclic multidentate podand ligands for transition metal complex catalysts in oxygenation with molecular oxygen[6] and found that palladium(II) complexes having 2,6-pyridinedicarboxamide-based tridentate ligands underwent the complexation with quinonediimines and modulated their redox properties.[7] In these palladium(II) complexes, the 2,6-pyridinedicarboxamide-based tridentate ligands and quinonediimines are organized into a mutually orthogonal orientation, and provide one coordination site available. We report herein a novel interlocked motif consisting of palladium(II) complexes having 2,6-pyridinedicarboxamide-based tridentate macrocyclic ligand and its application to rotaxane synthesis.[8,9]

Macrocycle **1**[10] was treated with palladium(II) acetate in acetonitrile at room temperature for 3 h to afford the corresponding palladium(II) complex **2** in 86% yield

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Keywords: [2]Rotaxane; Palladium; 2,6-Pyridinedicarboxamide; Macrocycle; End capping.

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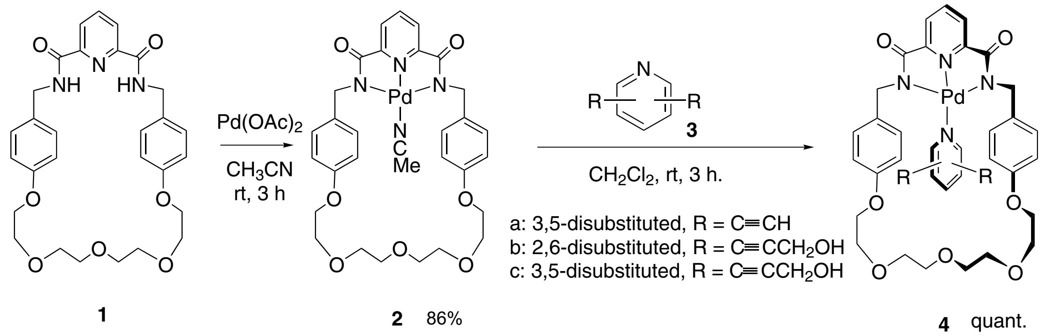

Scheme 1. Synthesis of Pd(II) complex **4**.

(Scheme 1). Compound **2** was allowed to react with 3,5-diethynylpyridine **3a**[11] in dichloromethane at room temperature for 3h to yield Pd(II) complex **4a** quantitatively. 2,6-Bis(3-hydroxy-1-propynyl)pyridine **3b**[12] and 3,5-bis(3-hydroxy-1-propynyl)pyridine **3c**[13] afforded quantitatively the corresponding Pd(II) complexes **4b** and **4c**, respectively. The ^{1}H NMR and FAB-mass spectra were consistent with their structures. The ^{1}H NMR spectra of palladium(II)-containing macrocycle **2**, 3,5-diethynylpyridine **3a**, and Pd(II) complex **4a** are shown in Figure 1. Upon complexation, the signals of the aromatic protons of 3,5-diethynylpyridine (e and f) showed considerable upfield shifts (ca. 1ppm and ca. 0.3ppm for e and f, respectively). These upfield shifts in ^{1}H NMR are attributed to the shielding effect of the *p*-phenylene groups in **2**. Similarly, the signals of the *p*-phenylene protons of macrocycle **2** exhibited upfield shifts (ca. 0.6 and 0.3ppm for c and d, respectively). These results suggest that the pyridine ring in the axle and the *p*-phenylene groups in the macrocycle moiety are arranged in close proximity.

Single crystals of **4a** suitable for investigation by X-ray crystallography were obtained from chloroform/*n*-hexane. The X-ray crystallographic analysis of a single crystal of **4a** revealed its interlocked structure, as shown in Figure 2.[14] The central palladium metal adopted a square-planar geometry, which is similar to that of palladium(II) complex having a pyridine-2,6-dicarboxamide-based podand.[7] It is suggested that the pyridine ring of the axle π-stacks with the two *p*-phenylene units. This π-stacking is consistent with the upfield shifts of their ^{1}H NMR signals.

4-Tris(4-*t*-butylphenyl)methylphenyl group was chosen as the end-capping group by CPK model inspection.

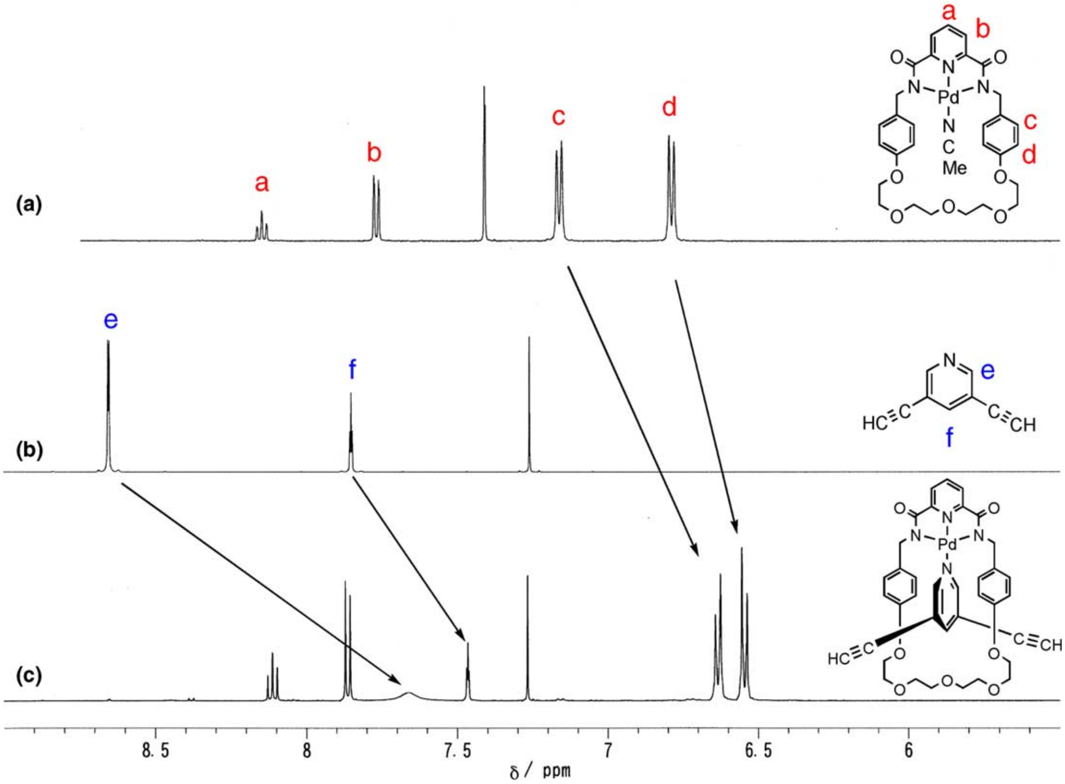

Figure 1. ^{1}H NMR spectra (500MHz, 298K) of (a) **2** in $CDCl_3/CD_3CN$ (70/30), (b) **3a** in $CDCl_3$, and (c) **4a** in $CDCl_3$.

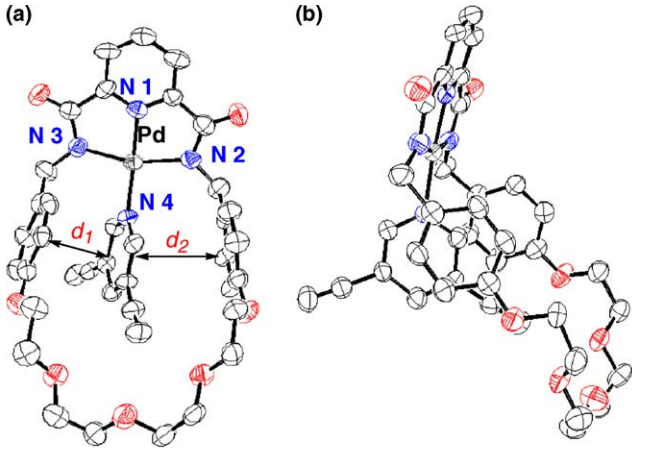

Figure 2. (a) Top view and (b) side view of the X-ray crystal structure of Pd(II) complex **4a**. Thermal ellipsoids are scaled to the 50% probability level. Selected bond lengths (Å): Pd–N1 1.957, Pd–N2 2.031, Pd–N3 2.024, Pd–N4 2.052; ligand bite angles (deg): N1–Pd–N2 80.50, N2–Pd–N3 160.6, N3–Pd–N4 98.20, N4–Pd–N1 174.7. d_1, d_2 (Å): 3.297, 3.463.

4-Tris(4-*t*-butylphenyl)methylphenyl isocyanate[15] reacted with **4b** in the presence of di-*n*-butyltin dilaurate in dichloromethane at room temperature for 20 h (Scheme 2).[16] The corresponding Pd(II) complex **5b** was obtained in 96% yield after chromatographic purification of the reaction mixture. On the other hand, **5c** was obtained in 89% yield by acid-catalyzed reaction of **4c** with the isocyanate. However, Pd(II) complex **5c** did not have interlocked structure, that is, the pyridine of its dumbbell unit coordinates to its macrocyclic Pd complex unit from outside of the macrocyclic plane. This was confirmed by demetallation experiments described below. The ^{1}H NMR, IR, and FAB-mass spectra of **5b** and **5c** were in good agreement with their structures.

In an attempt to remove the palladium(II) ion, **5b** was subjected to catalytic hydrogenation by use of 5% palladium on charcoal, hydrolysis in acetonitrile/water in the presence of triethylamine, and hydrolysis in 0.8 M hydrochloric acid. However, any reaction gave no **6b** but only a complicated reaction mixture. Demetallation of **5b** was achieved by treatment with carbon monoxide (50 atm) in methanol at 80 °C for 3 h to afford rotaxane **6b** quantitatively (Scheme 3). The structure of **6b** was confirmed by ^{1}H NMR, IR, and FAB-mass spectroscopies.[17,18] On the other hand, demetallation of **5c** gave an equimolar mixture of macrocycle **1** and its dumbbell **7** quantitatively. This unambiguously indicates that **5c** adopts a *side-on* coordination structure instead of the interlocked structure like **5b**.

In summary, a new interlocked motif was designed based on the palladium complexes having 2,6-pyridinedicarboxamide-containing tridentate macrocyclic ligand. Three Pd(II) complexes **4a–c** were synthesized quantitatively. Metal-free rotaxane **6b** was synthesized in a high yield by use of the present interlocked motif. This motif is applicable to the synthesis of other metal-based interlocked molecules such as catenanes and knots, which is ongoing in our group.

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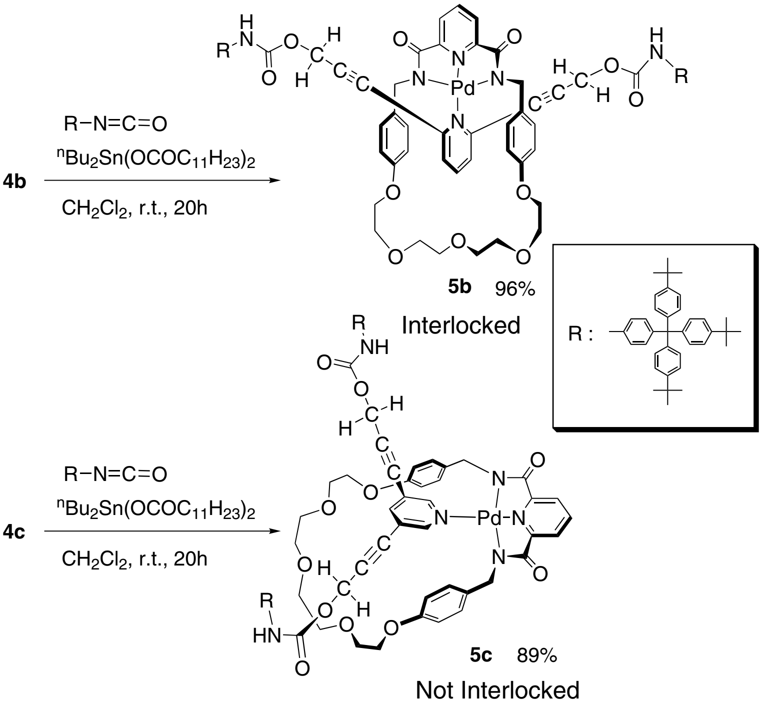
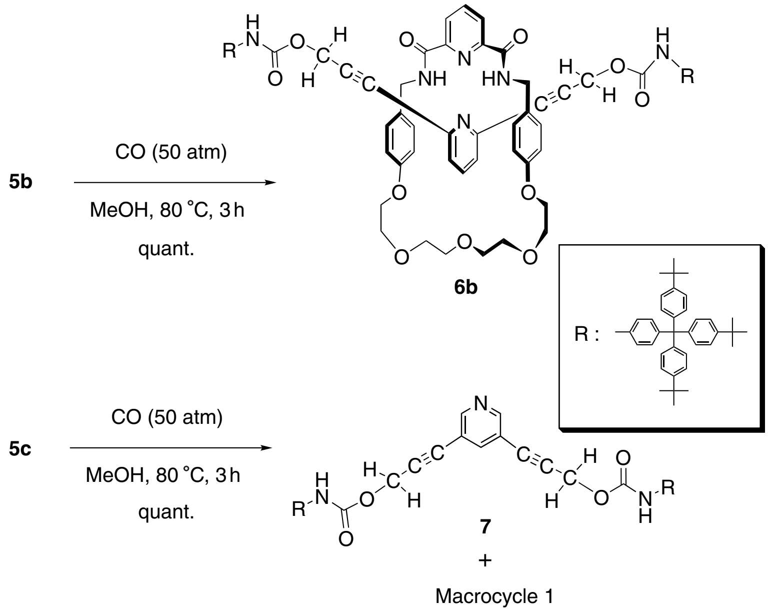


Scheme 2. Synthesis of Pd(II) complexes **5b** and **5c**.



Scheme 3. Demetallation of Pd(II) complexes **5b** and **5c**.

Ministry of Education, Science, Sports, and Culture of the Japanese Government.

References and notes

1. (a) Dietrich-Buchecker, C. O.; Sauvage, J.-P.; Kintzinger, J.-P. *Tetrahedron Lett.* **1983**, *24*, 5095–5098; (b) Dietrich-Buchecker, C. O.; Sauvage, J.-P.; Kern, J.-M. *J. Am. Chem. Soc.* **1984**, *106*, 3043–3045.
2. *Molecular Catenanes, Rotaxanes, and Knots*; Sauvage, J.-P., Dietrich-Buchecker, C., Eds.; Wiley-VCH: Weinheim, 1999.
3. Several catenates and rotaxanates have been synthesized by use of octahedrally coordinated metal centers, see: (a) Sauvage, J.-P.; Ward, M. D. *Inorg. Chem.* **1991**, *30*, 3869–3874; (b) Piguet, C.; Bernardinelli, G.; Williams, A. F.; Bocquet, B. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 582–584; (c) Leigh, D. A.; Lusby, P. J.; Teat, S. J.; Wilson, A. J.; Wong, J. K. Y. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 1538–1543; (d) Mobian, P.; Kern, J.-M.; Sauvage, J.-P. *J. Am. Chem. Soc.* **2003**, *125*, 2016–2017; (e) Pomeranc, D.; Jouvenot, D.; Chambron, J.-C.; Collins, J.-P.; Heitz, V.; Sauvage, J.-P. *Chem. Eur. J.* **2003**, *9*, 4247–4254.
4. (a) Amabilino, D. B.; Stoddart, J. F. *Chem. Rev.* **1995**, *95*, 2725–2828; (b) Jäger, R.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 930–944; (c) Breault, G. A.; Hunter, C. A.; Meyers, P. C. *Tetrahedron* **1999**, *55*, 5265–5293; (d) Hubin, T. J.; Busch, D. H. *Coord. Chem. Rev.* **2000**, *200–202*, 5–52; (e) Lee, J. W.; Samal, S.; Selvapalam, N.; Kim, H.-J.; Kim, K. *Acc. Chem. Res.* **2003**, *36*, 621–630.
5. *Molecular Machines and Motors (Structure and Bonding, 99)*; Sauvage, J.-P., Ed.; Springer: Heidelberg, 1999.
6. (a) Hirao, T.; Moriuchi, T.; Mikami, S.; Ikeda, I.; Oshiro, Y. *Tetrahedron Lett.* **1993**, *34*, 1031–1034; (b) Moriuchi, T.; Hirao, T.; Oshiro, Y.; Ikeda, I. *Chem. Lett.* **1994**, 915–918; (c) Moriuchi, T.; Hirao, T.; Ishikawa, T.; Oshiro, Y.; Ikeda, I. *J. Mol. Catal. A: Chem.* **1995**, *95*, L1–L5; (d) Hirao, T.; Moriuchi, T.; Ishikawa, T.; Nishimura, K.; Mikami, S.; Oshiro, Y. *J. Mol. Catal. A: Chem.* **1996**, *113*, 117–130.
7. (a) Moriuchi, T.; Bandoh, S.; Kamikawa, M.; Hirao, T. *Chem. Lett.* **2000**, 148–149; (b) Moriuchi, T.; Bandoh, S.; Ymiyaji, Y.; Hirao, T. *J. Organomet. Chem.* **2000**, *599*, 135–142; (c) Moriuchi, T.; Miyaishi, M.; Hirao, T. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 3042–3045; (d) Moriuchi, T.; Bandoh, S.; Miyaishi, M.; Hirao, T. *Eur. J. Inorg. Chem.* **2001**, 651–657; (e) Moriuchi, T.; Kamikawa, M.; Bandoh, S.; Hirao, T. *Chem. Commun.* **2002**, 1476–1477.
8. Leigh and co-workers have independently studied and recently reported the synthesis of a [2]rotaxane utilizing a 2,6-pyridinedicarboxamide-based Pd complex, based on a different protocol via macrocyclization Fuller, A.-M.; Leigh, D. A.; Lusby, P. J.; Oswald, I. D. H.; Parsons, S.; Walker, D. B. *Angew. Chem., Int. Ed. Engl.* **2004**, *43*, 3914–3918.
9. Part of this work was presented in *83rd Annual Meeting of the Chemical Society of Japan* held in Tokyo, March 2003; Abstract 3C7-01.
10. Macrocycle **1** was synthesized from the reaction of 4-cyanophenol and tetraethyleneglycol ditosylate in three steps. All new compounds dealt in the present work were fully characterized by ^{1}H NMR, IR, FAB-MS spectra, and elemental analyses.
11. Ng, S. C.; Novak, I.; You, X.; Huang, W. *J. Phys. Chem.* **1998**, *102*, 904–908.
12. Compound **3b** was prepared by the Sonogashira coupling of 2,6-dibromopyridine and 2-propyne-1-ol.
13. Compound **3c** was prepared from 3,5-dibromopyridine similarly to **3b**.
14. The crystallographic data reported in this paper have been deposited with Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-246458 for **4a**. Copies of the data can be obtained free of charge via <www.ccdc.cam.ac.uk/conts/retrieving.html> (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge, CB2 1EZ, UK; fax: +44 1223 336033; or deposit@ccdc.cam.ac.uk). Data for **4a**: $C_{76}H_{74}N_8O_{19}Pd_2$, FW 1616.26, triclinic, space group *P-1* (#2), a = 11.9089(2) Å, b = 16.4440(2) Å, c = 21.0275(5) Å, α = 70.786(3)°, β = 88.261(2)°, γ = 85.705(1)°, V = 3877.4(1), Z = 2, D_{calcd} = 1.384 g cm^{-1}, μ = 0.537 mm^{-1}, Mo Kα radiation (λ = 0.7107 Å), 33,839 reflections, 16,719 unique

reflections [$R_{\text{int}} = 0.034$], $R = 0.0540$, $wR = 0.0740$ for 10,995 observed data [$I > 3\sigma(I)$], GOF = 1.237.

15. 4-Tris(4-*t*-butylphenyl)methylphenyl isocyanate was prepared by the reaction of 4-tris(4-*t*-butylphenyl)methylaniline and triphosgene in refluxing toluene.
16. Furusho, Y.; Sasabe, H.; Natsui, D.; Murakawa, K.; Takata, T.; Harada, T. *Bull. Chem. Soc. Jpn.* **2004**, *77*, 179–185.
17. Mp 224–225 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 298 K): δ 9.05 (br t, $J = 6.0$ Hz, 2H, CON*H*), 8.33 (d, $J = 7.7$ Hz, 2H, py-3H and 5H of wheel), 7.89 (br s, 2H, OCONH of dumbbell), 7.88 (t, $J = 7.7$ Hz, 1H, py-4H of wheel), 7.58 (t, $J = 7.7$ Hz, 1H, py-4H of dumbbell), 7.23 (d, $J = 8.0$ Hz, 12H, ArH of endcap), 7.20 (d, $J = 7.7$ Hz, 2H, py-3H and 5H of dumbbell), 7.09 (d, $J = 8.7$ Hz, 12H, ArH of endcap), 7.03 (d, $J = 8.8$ Hz, ArH of endcap), 6.78 (d, $J = 8.8$ Hz, 4H, *p*-C_6H_4 of wheel), 6.45 (d, $J = 8.8$ Hz, 4H, *p*-C_6H_4 of wheel), 4.59 (s, 4H, $CCCH_2$ of dumbbell), 4.46 (d, $J = 6.0$ Hz, 4H, CH_2N of wheel), 3.93 (br s, 4H, OCH_2 of wheel), 3.73 (br s, 4H, OCH_2 of wheel), 3.65 (br s, 8H, OCH_2 of wheel), 1.29 (s, 54H, *t*-Bu); FT-IR (KBr) ν 3333, 3273, 1732, 1663, 1608, 1536, 1511, 1446, 1362, 1321, 1216, 1072, 823, 754 cm^{-1}; FAB-MS (mNBA matrix): *m*/*z*: 1783.3 [M+2H]; elemental analysis (%) calcd for $C_{116}H_{128}N_6O_{11}\cdot(H_2O)_{3.0}$ (1836.34): C, 75.87; H, 7.36; N, 4.58; found: C, 75.60; H, 7.44; N, 4.41.
18. No peak splitting of the ^{1}H NMR spectrum was observed for all the signals down to -50 °C. This indicates that the macrocyclic component moves along the dumbbell component with a high degree of freedom.